THE IMPACTS OF RURAL ROAD DEVELOPMENT ON FORESTS, GREENHOUSE GAS EMISSIONS, AND ECONOMIC GROWTH IN DEVELOPING COUNTRIES

CLIMATE ECONOMIC ANALYSIS FOR DEVELOPMENT, INVESTMENT AND RESILIENCE

Contract No.: AID-OAA-I-12-00038, Task Order AID-OAA-TO-14-00007

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DISCLAIMER

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ACRONYMS AND ABBREVIATIONS

BTU	British thermal unit
C	Carbon
CBA	Cost-Benefit Analysis
CEADIR	Climate Economic Analysis for Development, Investment, and Resilience
CGE	Computable general equilibrium
Cm	Centimeters
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GHG	Greenhouse gas
Ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
MT	Metric tons
NASA	National Aeronautics and Space Administration (United States)
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
tCO_2e	Metric tons of carbon dioxide equivalent
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
US EPA	United States Environmental Protection Agency

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EXECUTIVE SUMMARY

This literature review examines rural road construction, improvement, and use in developing countries and impacts on forests, greenhouse gas (GHG) emissions, and economic growth. Equipment and construction practices in road development have direct effects on GHG emissions. Other direct effects include GHG emissions from increased vehicle traffic on the roads. Road construction and improvement also creates indirect emissions by stimulating the clearing or degradation of neighboring forests. Deforestation is correlated with the presence of roads in developing countries, particularly in the tropics.

Road construction and improvement increase direct GHG emissions from equipment and vehicle use, though direct emissions tend to be smaller than the indirect emissions from deforestation associated with the roads. The indirect emissions of roads from deforestation or forest degradation can be up to 10 times larger than the direct emissions. However, most studies have only considered the direct effects of roads on deforestation. Roads can also have positive and negative social impacts, including increased transmission of diseases and increased opportunities for education and health care.

This report includes a framework for a qualitative assessment of deforestation and forest degradation impacts based on road project attributes. It discusses methods to quantify the GHG emissions from deforestation and forest degradation and also offers recommendations for reducing these impacts. One important approach is to establish or improve protected forest area conservation. Improved road network planning and use of rail transport can also reduce the direct and indirect impacts of greater accessibility.

1. INTRODUCTION

This literature review examines rural road construction, improvement, and use in developing countries and impacts on forests, greenhouse gas (GHG) emissions, and economic growth. It compares the GHG emissions from road development, vehicle use of roads, and deforestation and forest degradation associated with roads under different land tenure systems. It also summarizes the economic and social impacts of rural roads on local populations. It briefly addresses impacts on wildlife, the permanence of road impacts, and the relative impacts of roads and rail transport.

Rural roads can make remote areas more accessible for the expansion of human settlements and reduce the costs of bringing goods to and from markets. Economic benefits depend on how well the roads are sited and maintained. In some cases, there can be political or institutional motivations for building "roads to nowhere." Potential adverse environmental impacts include increased GHG emissions from deforestation, forest degradation, and other land use changes, as well as vehicle energy use. Motor vehicle use can cause air pollution, which is responsible for more than three million deaths per year, although mainly in urban areas (World Health Organization 2016a). Roads can also contribute to wildlife habitat losses and increased animal mortality from vehicle collisions. The environmental impacts can extend far beyond the land area occupied by roads. Roads can increase the feasibility and incentives for converting forests to agriculture or human settlements. They can increase opportunities for illegal and legal logging, mining, wildlife hunting, and fishing. Road development can affect ecosystem functions (such as hydrologic buffering and support for biodiversity), for considerable distances. Forests are a vital carbon sink, absorbing as much as 30 percent of global anthropogenic carbon dioxide (CO_2) emissions over the past few decades (Bellassen and Luyssaert 2014).

Deforestation refers to the conversion of forests to other land uses. There has been a net loss of 130-150 million hectares (ha) of forests over the past 15 to 25 years (Food and Agriculture Organization of the United Nations (FAO) 2016; Hansen *et al.* 2013). The World Wildlife Fund (2017) estimated that 46,000-58,000 square miles (119,000-1,150,000 km^2) of forest have been lost each year. This deforestation reduced global forest carbon stocks by almost 11 gigatons — over 1.5 times the total annual GHG emissions of the United States (Bellassen and Luyssaert 2014). Deforestation estimates do not include forest resource degradation (a reduction in the quality of forests in the absence of land use conversion). For example, a forest can be clearcut and remain classified as forestland, although this would involve forest resource degradation. Pearson, Brown, and Casarim (2014) estimated that GHG emissions from tropical forest degradation at 12 percent of the emissions from tropical deforestation.

Roads can drive deforestation because they increase access to forest resources and provide opportunities to convert forests to agricultural or human settlements (Ferretti-Gallon and Busch 2014). The most common use of converted forestland worldwide has been agriculture, which utilizes land for crops and pastures. Agricultural uses increased from four percent of ice-free land in pre-industrial times to 35 percent by 2000 (Goldewijk *et al.* 2011). However, not all the land converted to agriculture had been forest.

Data on the projected and actual amounts of deforestation associated with specific roads were generally inadequate. *Ex ante* estimates of direct deforestation from construction of a major road may be available if a good environmental impact assessment has been done. However, it is much more difficult to predict the indirect effects of roads on deforestation, and there have been few attempts to do so. Barni, Fearnside, and Graça (2009) projected the direct and indirect effects of paving BR-319 — an 877-km road between Porto Velho and Manaus in Brazil — and estimated that it could result in more than 5,000 km^2 of deforestation and emissions of almost 100 million tCO_2e.

Forest degradation refers to a reduction in the quality of a forest due to changes in the amount or composition of biomass that affects its ability to provide economic and ecosystem services. Forest degradation may have anthropogenic causes (human activities, such as logging) or environmental events (such as natural fires or pests and diseases). Forest degradation can release stored carbon, reduce the capacity of trees to take up CO_2 from the atmosphere, cause the loss of species, reduce yields of wood products, and damage habitat quality or watershed functions. Forests can recover over decades if further disturbances do not occur and the land is not converted to non-forest uses (Thompson *et al.* 2013).

Section 2 discusses the costs and benefits of roads. Section 3 addresses the impacts of road infrastructure on deforestation and forest degradation, while Section 4 focuses on greenhouse gas emissions and other environmental and social impacts. Section 5 summarizes the relative magnitude of GHG emissions from road construction, land use changes, and increased road traffic. Section 6 provides an overview of tools and data analysis methods for estimating the GHG impacts of roads. Section 7 discusses options for reducing the negative impacts of roads.

2. COSTS AND BENEFITS OF RURAL ROADS

Table 1 lists common types of direct and indirect costs and benefits from construction or improvement of rural roads. The environmental costs are often excluded or inadequately addressed in economic analyses.

TABLE 1. Positive and Negative Impacts of Rural Road Construction or Improvements

	Positive Impacts	Negative Impacts
Direct	• Reduced transport costs and travel time • Increased transport reliability • Easier access to healthcare, education, and other public services • Access to new markets for buying and selling products and services	• Land acquisition and clearing costs • Road construction material and labor costs • Dust and noise during construction • GHG emissions from land clearing and construction • GHG emissions and air pollution from increased vehicle traffic • Vehicle noise • Deaths and injuries from vehicle accidents • Plant and animal habitat loss and animal roadkill
Indirect	• National or subnational economic growth • Poverty alleviation • Increased community resilience	• Deforestation and forest degradation from increased legal and illegal logging, agriculture, human settlements, and mining • GHG emissions from associated deforestation and forest degradation • Habitat loss • Increased spread of invasive species • Reduced ability of forests to minimize soil erosion and regulate water quantity and quality

De Luca (2007) reviewed over 80 studies in developing countries in the tropics between 1990 and 2006 and found that rural road construction and improvement increased economic activity. The gains varied with the baseline level of economic development and productive capacity of the land for agriculture. Andersen and Reis (2015) found an association between the length of rural roads and rural agricultural output in Brazil. Warr *et al.* (2010) estimated that improving an existing road to all-weather use in Laos could reduce poverty rates by five to 13 percent. Bell and van Dillen (2014) concluded that construction of all-weather roads in India could increase rural household incomes by five percent, reduce school closure days due to inaccessibility, and increase access to health care.

A review for the World Bank found that road construction had more economic benefits in areas with low baseline levels of economic development. Also, feeder road construction typically had higher economic returns and a greater effect on poverty alleviation than major highway construction (De Luca 2007). Although not explained in the study, it is possible that people who are relatively far from any road have lower baseline incomes and less access to markets than those closer to a low-standard road. Areas where highway construction is likely may already benefit from other existing roads. It is also much less expensive to construct low-standard roads than highways. However, the economic benefits of roads vary with the location, historical context, and timeframe of the analysis. Extrapolations from prior studies to other locations and time periods might not be valid.

The specific economic and environmental impacts of new and improved roads should be assessed before major investments are recommended, financed, or implemented.   These assessments should consider how well the existing road networks are likely to function under various projected scenarios.

BOX 1. Soil Carbon Emissions

Most cost-benefit roads analyses have not accounted for soil carbon emissions associated with deforestation. Soils can have triple the average level of CO_2 currently in the atmosphere. Between 30 and 50 percent of the carbon in the top 30 cm of soil may be lost in the conversion of forests to agriculture (Paustian *et al.* 2016). Even more soil carbon is lost when it is converted for a non-vegetation purpose (Wick *et al.* 2009). Where data allow, cost-benefit analyses should value or at least quantify soil carbon emissions from deforestation and other impacts (such as soil erosion, nutrient losses, increased runoff and sedimentation and damage to soil structure that reduce productivity) as well as their estimated monetary values.

Transportation is a derived demand rather than an end in itself. The purpose of the transportation system is to allow other sectors of the economy to operate efficiently and reliably. Governments often place too much emphasis on temporary spending and jobs in road construction to achieve near-term political gains. There are generally many alternatives for meeting the demand for transportation that governments should consider. They should also compare the net present value of returns from road construction or improvement to those of other public investments.

In some cases, road improvements can reduce GHG emissions per unit weight and distance of goods transported, particularly in urban areas with high traffic congestion. However, GHG emissions may still increase if the total volume of goods transported increases. Taptich, Horvath, and Chester (2015) described methods for estimating GHG emissions and mitigation opportunities from road transport.

Road investments in forested areas often lead to deforestation and forest degradation that increase GHG emissions and reduce ecosystem functions, such as hydrologic buffering and habitat for biodiversity. The effect on GHG emissions depends on the extent and timing of the deforestation or forest degradation, the biomass density of the cleared or disturbed forest, and mitigating actions such as replanting or allowing natural regeneration.

In general, existing economic analyses of roads have not addressed GHG emissions alongside other environmental impacts. It is important to consider GHG emissions and other environmental impacts because they could change decisions and the desirability of a proposed investment as compared to other road or non-road alternatives. If these impacts are not included in a cost-benefit analysis (CBA), they should be considered separately in decision making and reduced or mitigated, where feasible.

GHG emissions have global impacts that vary by location, are complex, and are subject to considerable uncertainty. These impacts can result in long-term costs. As with financial costs and benefits, a discount rate is often used to convert the future costs to a present value. However, there is considerable debate over the appropriate discount rate level and whether the same rate should be used for monetary costs and benefits and longer term GHG impacts. USAID (2015) recommends a 12 percent real discount rate for economic analyses of USAID development projects. At a 12 percent discount rate, any costs incurred more than 20 years into the future have a negligible present value. However, it is clear that societies value what happens beyond 20 years in the future for themselves and future generations. For intergenerational equity, some economists have recommended a zero discount rate or a lower rate for long-term environmental costs rather than short-term and medium-term monetary returns (Goulder and Roberton 2012).

3. INFLUENCE OF ROADS ON DEFORESTATION AND FOREST DEGRADATION

Rural road construction or improvement can open up new areas for logging that were previously inaccessible or too costly for felling and extracting timber or woodfuels. Similarly, rural roads can make farming more profitable by reducing the costs of transporting agricultural inputs and products and increasing incentives for converting forests to agriculture. New or upgraded roads also increase the accessibility of forestland to expand human settlements. Population and income growth may increase pressures for deforestation and additional road construction (Geist and Lambin 2002). Ferretti-Gallon and Busch (2014) and Reis and Guzmán (2015) found that population growth was an important driver of deforestation, but did not address road construction or improvement as a driver of population growth.

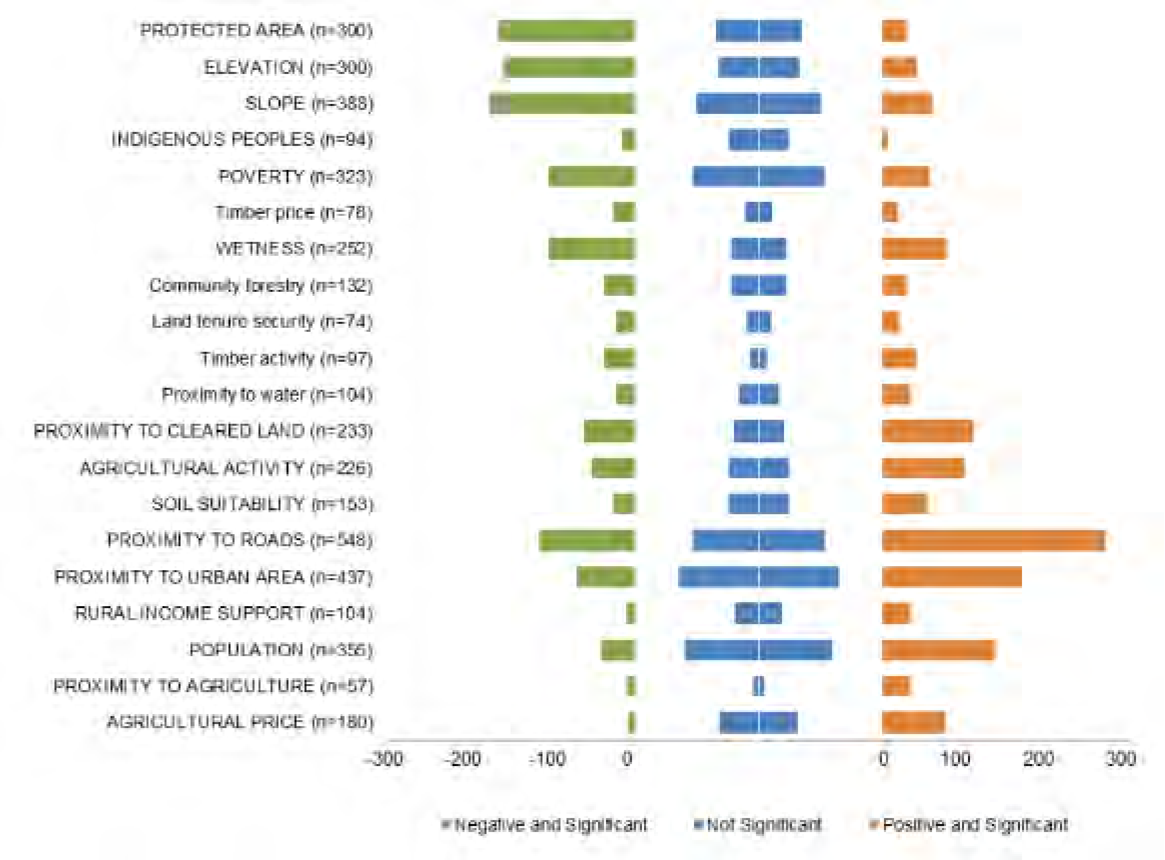
Road construction has been associated with subsequent increases in deforestation or forest degradation, including areas many kilometers from the road. However, differences in the definition of a road and the spatial and time boundaries of the analysis affect the comparability of different studies. There may also be other confounding factors, such as the location of other roads. For example, a site several kilometers from a national highway might have a low deforestation rate if there are no feeder roads nearby, whereas the deforestation may be higher if the site is served by feeder roads.

The amount of deforestation or forest degradation resulting from road construction or improvement depends on the design and construction of the road; site-specific environmental conditions; and economic, social, political, and geographic factors. In general, there is a positive association between deforestation and the road's proximity to urban markets (Ferretti-Gallon and Busch 2014; Barni, Fearnside, and Graça 2009; Berenguer 2013; Gonzalez, Kroll, and Vargas 2014). There is also a positive association between deforestation and the forestland's suitability for agriculture (Ferretti-Gallon and Busch 2014; Etter *et al.* 2006).

Figure 1 compares the magnitude and direction of the factors correlated with deforestation, based onthe Ferretti-Gallon and Busch (2014) global meta-analysis. The strongest positive correlation was between the proximity of roads and deforestation. Proximity to urban markets had the second highest positive correlation with deforestation. Deforestation rates tended to be lower in protected areas, in higher elevations, and on steeper slopes. Rates are also higher in areas with larger populations. These conclusions only pertained to deforestation since forest degradation is more challenging to track with remote sensing data.

The amount of deforestation associated with road improvement varies with the type of road and its use, proximity to forests and population centers, forest characteristics, land tenure and forest rights, policy and regulatory environments, and the enforceability of laws. Reid (1999) reported approximately 2 km^2 of deforestation per kilometer of a gravel road in a sparsely populated area in Bolivia. Over 50 years, there has been more than 100 km^2 of deforestation per kilometer of paved highway between major population centers in the Amazon (Soares-Filho 2006).

FIGURE 1. Global Meta-Analysis of Factors Correlated With Deforestation[a]



[a] The scale shows the number of studies.

Source: Ferretti-Gallon and Busch (2014).

Gonzalez, Kroll, and Vargas (2014) studied historical land use changes between 1989 and 2005 in a 5,600 km^2 area in Selva Central, Peru, using satellite imagery and ground measurements. During this period of over 15 years, the net deforestation rate was 0.3 percent per year and the forest degradation rate was 0.2 percent per year. They estimated that this deforestation and degradation increased net emissions by 1.6 metric tons of carbon (5.9 million tCO_2e). This analysis also found that the probability of deforestation was most strongly correlated with the distance to roads; other explanatory variables considered were elevation, slope, and distance to non-forest areas. The probability of deforestation tripled in close proximity to a road; probability was 10 percent at a five km distance from a road and 30 percent for sites with adjacent roads. Distance to towns or villages had a similar effect on the probability of deforestation. This study, however, did not quantify the effects of distance and other factors on the probability of forest degradation. It also did not quantify the effects of protected areas, though the three protected areas in the study area had no net deforestation and little forest degradation over the time period.

Deforestation associated with roads often occurs in distinctive patterns. On relatively flat terrain, secondary roads are often built perpendicular to main roads and deforestation increases around both the main road and secondary roads. This "fishbone" pattern of roads and deforestation has been observed in multiple areas in Brazil (Geist and Lambin 2002; de Oliveira Fihlo and Metzger 2006). Figure 2 shows this fishbone pattern of deforestation extending from a main road in the Brazilian Amazon.

FIGURE 2. Fishbone Deforestation Associated with Roads in the Brazilian Amazon

Photo source: NASA Jet Propulsion Laboratory (2006).

Not all studies have found that deforestation rates were correlated with distance to roads; local conditions such as agriculture can also drive rates. For example, Viña, Echavarria, and Rundquist (2004) examined satellite imagery and found that deforestation rates on the Colombian side of the Ecuador border between 1973 and 1996 were higher in areas farther from roads. More than 70 percent of deforestation on the Colombian side of the border occurred beyond five km from a road. By contrast, 90 percent of the deforestation on the Ecuadorian side was within five km of a road. The different pattern of deforestation in Colombia resulted from the planting of coca in more remote areas to reduce the likelihood of government detection.

As an area loses its forest cover, the deforestation rate decreases because there is less forest left to convert to other land uses. As that happens, further expansion of the road network will no longer have much effect on local deforestation, although it may increase access to more distant areas.

3.1 CONVERSION OF FORESTS TO AGRICULTURE

BOX 66. Land Tenure and Deforestation

The relationship between land tenure systems and deforestation is complicated and may vary. Nepstad *et al.* (2006) and Nagendra *et al.* (2008) found that collective ownership of land and ownership by indigenous peoples was associated with lower rates of deforestation. Ricketts *et al.* (2010) concluded that the probability of deforestation in the Brazilian Amazon was seven to 11 times higher outside indigenous lands and protected areas. Conversely, Rueda (2010) and Ferretti-Gallon and Busch (2014) found that collective ownership increased deforestation, possibly by facilitating investments in land development.

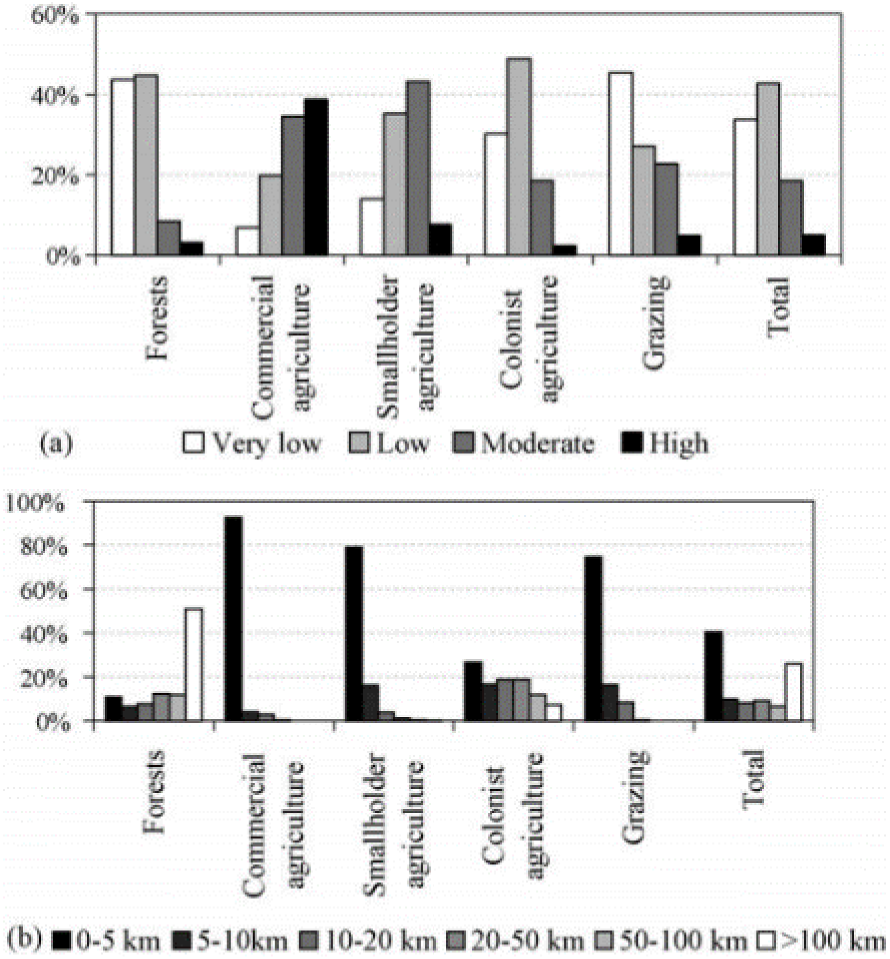
Bottazzi and Dao (2013) considered the relationship between land tenure and deforestation along with historical and political factors affecting the allocation of collective land rights. They found that lands with less economic potential had a lower risk of deforestation and were more likely to be assigned

Much of the deforestation associated with roads is due to agriculture. Construction or improvement of rural roads can make land more profitable for agriculture. In the early nineteenth century, von Thünen hypothesized that the value of agricultural land depended on its productivity and transportation costs for inputs and products. Improved road networks that facilitate agricultural goods transportation may make it more likely that forestland will be converted to agricultural land. Chomitz and Gray (1996) confirmed this hypothesis in southern Belize.

Li *et al.* (2012) concluded that the implementation of a plan for new roads in the Democratic Republic of Congo would reduce the national forest cover by two percent, mainly resulting from the conversion of forests to agriculture land. They estimated that this would cause a one-time release more than one billion tCO_2e but did not consider additional future effects.

Using satellite data and land cover and soil maps, Etter *et al.* (2006) confirmed that 80 percent of Colombia's forestland had low soil fertility (Figure 3). Most of the more fertile land had already been converted for crops or grazing use. About 50 percent of the remaining forest in Colombia was more than 100 km from a road.

FIGURE 3. Relationship Between the Main Land Use Types in Colombia to Soil Fertility, and Distance to Roads



Source: Etter *et al.* (2006).

Patarasuk (2013) used Landsat images to examine the effects of roads on deforestation in Thailand between 1989 and 2006. Approximately 15 percent of the study area was converted from forest to agricultural land over that time. The author concluded that the most important driver of deforestation was the increase in the length of the road network. However, the connectivity of the road network did not increase with length.[1] As a result, better planning could have increased road network connectivity with less road construction and deforestation.

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[1] *Road network connectivity* is the ratio of the links between the nodes in the road network and the maximum potential number of links. The links are roads and nodes are as the intersections of roads.

3.2 FOREST DEGRADATION

New or improved roads can increase forest degradation by making it easier to access forest resources and reducing the transport costs of removing wood and non-wood forest products. If a forest is clear cut, but allowed to regenerate, it would be classified as forest degradation, rather than deforestation. Natural tropical forests contain a large number of tree species and only a small number of species may be commercially valuable timber. However, the process of logging, extracting, and transporting the few commercial species can cause considerable damage to the other species left behind. Forest degradation can also adversely affect plant and animal species (especially those specialized for life in the interior of closed-canopy forests) and increase the risk of invasive, non-forest, or nonnative species.

Forest degradation reduces carbon stocks and the atmospheric uptake of carbon. The carbon losses from logging and extraction damage often exceed the carbon removed in the harvested timber. Asner *et al.* (2010) calculated that degraded forests had 70 percent less biomass than other forests in the area. Berenguer *et al.* (2014) measured carbon stocks in disturbed forest that had undergone selective logging or understory fires and found that disturbed forests had 40 percent less aboveground carbon than undisturbed forests. Pearson, Brown, and Casarim (2014) reviewed data from Belize, Bolivia, Brazil, Guyana, Indonesia, and Republic of Congo between 1999 and 2012 and found that nearly 80 percent of the carbon lost from selective logging was from the damage to surrounding vegetation and the establishment of logging roads.

Gatti *et al.* (2015) compared primary forests to selectively logged forests in Sierra Leone, Ghana, Cameroon, and Gabon; some of the logged plots had not been cut for 30 years or more. In general, the researchers found no significant differences in average tree height or species diversity, but there were significant differences in the amount of aboveground biomass and the average tree size (which refers to a tree's diameter at breast height). Gatti *et al.* did not report the magnitude of the differences in above ground biomass.

Laurin *et al.* (2016) studied four national parks and protected forest areas in Ghana with varying levels of degradation: 1) a national park with almost no logging; 2) a national park with little logging but frequent natural disturbance from fire, drought, and elephants; 3) a forest reserve that had been selectively logged between 1980 and 1990; and 4) a forest reserve with frequent illegal timber harvest, including selective logging. All of the study plots had some level of protected status, but the national parks had the lowest level of logging. The study found that the two selectively logged plots had about half of the aboveground biomass of the others (150 metric tons/ha versus 300 metric tons/ha). The selectively logged areas also had lower soil carbon stocks of approximately 100 metric tons/ha while the unlogged sites had 125-150 metric tons of carbon per hectare. These differences persisted even though the logging had largely ended 25 years earlier. Selective logging can have more negative impacts than other types of natural disturbance, such as fire and drought.

Forest degradation can also result from woodfuel use (charcoal and fuelwood). Bailis *et al.* (2015) estimated that more than half of all wood harvested worldwide was used for fuel and that 27-34 percent of that harvest was unsustainable. However, they concluded that biofuels accounted for only two percent of global GHG emissions.

BOX 97. Rail, Boat, and Air Transport for Freight

Rail has lower GHG emissions per ton-mile of freight transported than trucks. Rail transport typically required 296 British thermal units (BTUs) per ton-mile compared to 1400 BTUs for trucks (calculated from Davis et al., 2015 and Hosseini and Shiran, 2011).

Furthermore, Viana *et al.* (2008) noted that train tracks passing through forests to connect market centers often result in less deforestation than highways because rail allows greater control of access to neighboring lands.

However, rail systems are not as dense as road networks and freight transport by rail usually also requires trucking to or from rail lines. The apparent GHG benefits of rail over trucks may be lower after accounting for these intermodal transfers. Capital costs are generally higher for a new rail link than a new highway of similar capacity, but operating costs may be lower for rail.

If there are navigable waters, boat transport is likely to be less costly than rail or highway construction. However, many areas do not have navigable waters. Boat transport can be slower than trains or trucks and may have higher handling costs for heavy freight. Air shipments may be feasible for lightweight, high-value products — especially those that are perishable and benefit from faster travel times. However, small and medium planes are more expensive to buy and operate than road vehicles. Airplanes and boats generally have limited value as substitutes for rural roads.

Charcoal is a convenient cooking fuel in urban areas because it is easy to transport long distances, store, and use. It may also be preferred over kerosene, bottled gas, or electricity for food taste. Charcoal is a purchased fuel that is used by lower- and middle-income urban households. There is a large net energy loss in converting wood into charcoal (approximately 50 percent), even after accounting for the higher efficiency of charcoal stoves than wood stoves. Fuelwood is often collected for local sales or use in rural households. Whole live trees are often felled for commercial charcoal production. However, fuelwood is often taken from fallen wood or pruning byproducts of trees that are left standing to regrow.

Specht *et al.* (2015) estimated that 76 percent of the 520,000 people living in the northern portion of the Brazilian Atlantic Forest used fuelwood as their main cooking fuel, resulting in forest degradation equivalent to the clearing of 2,000 ha of forest per year.

Road development can increase forest fragmentation. Small, fragmented forests may be more affected by heating and drying due to greater exposure to open areas. Laurance *et al.* (2011) found that forest fragmentation increased tree mortality in the Amazon, including that of large trees with a diameter at breast height of 60 cm or more. These large trees are typically replaced by faster-growing pioneer trees and lianas that store less carbon. The 2011 study estimated the edge-related forest loss in the Amazon at 550 million tCO_2e per year, which was more than the total carbon emissions in the United Kingdom in 2015 (496 million tCO_2e).

Forest fragmentation also has negative impacts on biodiversity, reducing animal habitats, pollination, and seed dispersal. Fragmented forests are also more susceptible to changes in microclimate and invasive species (Arroyo-Rodriguez *et al.* 2017). Some islands in Thailand, for example, had a near total loss of native, small mammals from forest fragments smaller than 10 ha within five years and from 10 to 56 ha fragments within 25 years due in part to the invasion of non-native rat species (Gibson *et al.* 2013).

3.3 FORESTRY PRACTICES THAT REDUCE DEFORESTATION FROM ROADS

Good forestry practices can reduce deforestation by increasing the financial returns from forests relative to agriculture (Ferretti-Gallon and Busch 2014). Although logging reduces short- and medium-term forest carbon stocks, forests can re-accumulate the carbon over a longer period if the trees are allowed to grow back to maturity. Consequently, the long-term effects of sustainable forestry may create lower GHG emissions than other land uses.

Road construction or improvement can increase the net returns from both forestry and agriculture by decreasing transport costs, though the net effect may favor conversion to agriculture. The expected uses of a road affect the type and standard of construction and the persistence of its impacts on forests. Temporary roads to support forestry operations have a low standard of construction since they may only be used for one logging cycle. High-standard roads are generally built for non-forestry purposes and are expected to remain in use for decades. As a result, they are associated with more deforestation than temporary roads (Kleinschroth *et al*. 2015). Most logging roads in the Congo basin have reverted to vegetation within four years and none used in the study area in 1997 were still in use in 2013. Within 20 years, the areas around the temporary logging roads in the Congo were indistinguishable from the surrounding forest.

FIGURE 4. Road Transport of Selectively Harvested Logs in Southern Cameroon

Photo credit: Gordon Smith, 2012.

4. GREENHOUSE GAS EMISSIONS AND ENVIRONMENTAL IMPACTS FROM ROAD CONSTRUCTION AND USE

4.1 GHG EMISSIONS FROM ROAD CONSTRUCTION

GHG emissions from road construction stem from the manufacturing and transport of road construction materials, fuels used in road construction equipment, and the removal of biomass and soil carbon. Most studies of GHG emissions from road construction have been done in developed countries in the temperate zone. The largest direct emissions from road construction activities typically result from heavy machinery. A study in South Korea found road construction emissions to be 265 to 1,033 tCO_2e per lane-km constructed, depending on the use of bulldozers, excavators, and other machinery (Kim *et al.* 2011). Road construction emissions can be reduced by using fuel-efficient equipment of the appropriate scale and organizing construction processes for greater efficiency (e.g., preparing surfaces for work, moving earth and materials downhill, and managing traffic if part of the road remains in use). The type of road, terrain, and accessibility also affect GHG emissions. More energy-intensive, earth moving equipment use may be needed in areas with steep or irregular terrain.

There are also indirect emissions from manufacturing and transport of road construction materials. Hanson, Noland, and Cavale (2012) found that warm-mix asphalt had lower GHG emissions per lane-km over the 30-year expected life of a highway (473 tCO_2e) than various concrete formulations (1,131 to 1,440 tCO_2e). The GHG emissions from asphalt roads were lower despite the fact that, unlike concrete roads, asphalt roads need to be paved twice during this time period. These estimates included the indirect emissions from manufacturing and transport of paving materials and the direct emissions from application of the materials in construction. However, these estimates did not account for the CO_2 absorbed during carbonation of the concrete after road construction, a carbon sink. Carbonation of concrete can absorb up to 3.8 tCO_2 per cubic meter over 100 years (Barandica *et al.* 2013). At 2,346 cubic yards of concrete per lane-mile (Hanson, Noland, and Cavale 2012) a concrete road can absorb more than 1,200 tCO_2 per lane-km over its 30-year life. Larrea-Gallegos, Vazquez-Rowe, and Gallice (2017) estimated the life-cycle emissions of a 45-km section of gravel road in Peru at 90 tCO_2e/lane-km from construction and 10 tCO_2e/lane-km/year from expected road use by fewer than 200 vehicles per day.

Huang, Hakim, and Zammataro (2013) developed a life-cycle assessment model for GHG emissions from road construction and applied data from construction or improvement of roads in four countries. The model predicted that the addition of a new lane to an existing one-lane road in India would release 897 tCO_2e per kilometer. It also predicted that construction of a four-lane road in the United Arab Emirates would generate 2,406 tCO_2e per lane-kilometer.

FIGURE 5. Road Construction Through a Forest in the Democratic Republic of the Congo

Photo credit: Flickr/Internet Archive of Book Images.

Few studies on the GHG emissions from road construction have accounted for the effects of land use changes in the area occupied by a road, road bed, shoulders, cuts and fills, and intersections. Kim *et al.* (2012) found that GHG emissions from land cleared for road construction ranged from 88 to 385 tCO_2e per lane-km in South Korea. However, the study excluded GHG emissions from additional land clearing induced by the road. Barandica *et al.* (2013) examined four road projects in Spain and found that equipment use generated 50-70 percent of total construction emissions, while land cleared for the road was less than 10 percent of the total.

The amount of land cleared for a road depends on the road's length, its average width, the space needed to move equipment and materials, and the prior land use. The road design and construction plans should specify the first three factors. The land's prior uses may be listed in these plans or in an environmental impact assessment, if one has been prepared. The environmental assessment may or may not include the carbon content of the forest or other biomass cover; nearly all of the carbon in the cleared biomass will be emitted as carbon dioxide. While there will be some methane emissions if the biomass is burned, these are generally small relative to CO_2 emissions and might be offset by any biomass carbon that remains sequestered.

The Intergovernmental Panel on Climate Change (IPCC)'s guidance on national GHG accounting contained default carbon stock estimates per hectare for 15 climate domains and ecological zones including tropical rain forests, subtropical dry forests, and temperate mountain systems (IPCC 2006). Where available, country- or location-specific studies are likely to yield more accurate estimates of forest carbon stocks.

The removal and piling of soil along road margins and the breaking up of soil aggregates can release 65 percent of the soil's organic carbon content by exposing it to microbial respiration, in turn reducing carbon sequestration from plant growth (Wick *et al.* 2009). The GHG emissions from directly affected land can be estimated by multiplying the non-vegetated surface area (including the road shoulders and margins) by the carbon emissions from the vegetation and soil that results from road building.

If the road margins are allowed to revegetate, the continuing soil carbon loss may stop. Over time, the soil carbon in vegetated rights-of-way can approach the stocks of undisturbed sites with similar vegetation. The IPCC (2006) provides default estimates of soil carbon stocks to 30-cm depth for major soil textures in various climate zones. However, national or local studies would likely provide better estimates of soil carbon stocks. Though the rate of soil carbon buildup after a disturbance is nonlinear and location-specific, the IPCC recommended a default assumption of 20 years before soil carbon stocks are restored if the vegetation is allowed to regrow.

4.2 GHG EMISSIONS FROM ROAD USE

Road use typically generates substantially more GHG emissions than road construction, but the effects are complex since a new or improved road may displace or increase traffic on other roads. Transportation is the largest source of GHG emissions in many developing countries and can represent more than 60 percent of a country's total inventory (World Atlas 2017).

The amount and composition of traffic on new or improved roads and the resulting GHG emissions can vary considerably by location, type of road, trade patterns, and transport alternatives. The number of vehicle trips tends to increase as the areas accessible from the road undergo further development. Relatively few specific quantitative data were available on the increase in traffic from construction or improvement of *rural* roads in developing countries. However, new lanes added to congested urban highways in developed countries and often become more congested within three years (Litman 2016).

GHG emissions from vehicle road use can be estimated by multiplying the projected use of different types of vehicles by their average emission rates. This calculation should specify baseline emissions and projected emissions with and without the road should be specified. Data on national GHG emissions from transportation can be obtained from a country's GHG inventory submitted to the United Nations' Framework Convention on Climate Change. However, downscaling national data or assumptions to estimate the GHG emissions from a particular road is problematic.

GHG emissions from increased road use depend on the amount, type, size, age, fuel grade, and condition of vehicles as well as travel speed and traffic congestion. Data on motor vehicle emissions are available in developed countries, but they are likely to be substantially higher in developing countries where the vehicle fleet is older, less well maintained, includes a smaller percentage of electric or hybrid vehicles, and uses lower-grade fuels. In the U.S., GHG emissions from passenger cars averaged 0.255 kg CO_2e/km (U.S. Environmental Protection Agency (EPA) 2016). The GHG emissions of passenger vehicles in the U.S. varied across models by a factor of more than three. Davis, Diegel, and Boundy (2015) estimated GHG emissions from heavy trucks in the U.S. at 1.0875 kg CO_2/km based on U.S. Department of Energy fuel economy data.

Road design decisions can affect GHG emissions from vehicle use. Rolling resistance — a function of pavement roughness and stiffness — may have the largest effect (Santero and Horvath 2009). Another important factor is the design of road and traffic controls for reducing traffic delays.

Widening an existing highway can increase GHG emissions by increasing vehicle-miles traveled and inducing other types of development. Williams Derry (2007) estimated that adding a new lane to a highway in locations across the U.S. would increase GHG emissions by more than 100,000 tCO_2e per mile over 50 years. Although average vehicle fuel efficiency has improved since this estimate, the net emissions rate may not have changed due to increases in vehicle-miles traveled and traffic congestion. The net effect will also vary locally.

4.3 IMPACTS OF ROADS ON WILDLIFE

Roads can decrease wildlife populations and diversity due to collisions with vehicles, habitat loss, and fragmentation. An increase in animal road deaths may be larger with construction of new roads than with the expansion of existing roads (Rhodes *et al.* 2014). Reptiles are often attracted to roadsides for basking in the sun, making them susceptible to collisions with vehicles and other human interference.

Even relatively narrow clearings from roads can cause significant habitat fragmentation and adverse edge effects on wildlife. Edge effects are changes in the quantity and quality of habitat due to roads or other land use changes. Forests within 100 m of a road clearing have greater daily fluctuations of light, temperature, and humidity and are typically drier and hotter than contiguous forests (Goosem and Laurance 2009). Reptiles and amphibians are particularly susceptible to microclimate changes from road clearing because of their high skin permeability (Andrews, Gibbons, and Jochimsen 2008).

Edge effects can also increase wind disturbance and desiccation stress. Forest populations are less vulnerable to edge effects if road clearings are smaller than 20 meters wide (Laurance, Goosem, and Laurance 2009). Road deaths may be larger, however, on narrow roads as some animals are more likely to cross them than wide roads. Beetles, flies, ants, bees, butterflies, amphibians, reptiles, birds, bats, and small and large mammals tend to avoid road clearings in tropical forests that are wider than 30 m (Laurance, Goosem, and Laurance 2009). Andrews, Gibbons, and Jochimsen (2008) noted that roads reduce genetic diversity by isolating populations. Hunters and gatherers gain increased access to an area within a five- to ten-kilometer radius of a road.

Ahmed *et al.* (2014) found that bird populations were higher and bird species diversity greater in forested areas in the eastern Brazilian Amazon with few roads (2014). Negative impacts on bird populations and species diversity may be more strongly associated with the presence of roads, rather than the reduction in forest cover.

4.4 IMPACTS OF ROADS ON AIR QUALITY

This report focuses on the GHG impacts of rural roads, but road transport also contributes to emissions of fine particulates, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). More than 6.7 billion people (92 percent of the world's population) live in areas where air pollution exceeds recommended limits. Air pollution contributed to more than three million premature deaths per year (World Health Organization 2016a).

There is extensive literature on air pollution from road transport in urban areas of developing countries (Colvile *et al.* 2001; McGranahan and Murray 2003; Han and Naeher 2006; Liaquat *et al.* 2010; Mao *et al.* 2012; and Shrivastava, Neeta, and Geeta 2013). The construction or expansion of roads may induce new traffic or divert it from other roads that may be more congested or less direct. Motor vehicles can also contribute to air pollution in rural areas with poor air quality from industry, mining, biofuel, or coal combustion (Umoh and Peters 2014; Singh *et al.* 2014).

4.5 SOCIAL IMPACTS OF ROADS

Rural roads can have negative social impacts, including increased drug and human trafficking and the loss of formal or traditional land tenure or use rights for low-income populations (including indigenous or marginalized communities). Increasing the accessibility of relatively isolated communities can alter their social structure, dynamics, and disease transmission. Eisenberg *et al.* (2006) found that new roads increased the transmission of diarrheal diseases. However, roads can also have positive social impacts; De Luca (2007) reviewed 31 studies from developing countries in various regions and concluded that road construction or improvement increased the proportion of the population with access to health care, sanitation, electricity, and education services. De Luca (2007) noted that better roads can increase the mobility and safety of women who can travel by motor vehicles instead of walking.

Perz *et al*. (2012) noted that roads can increase the resilience of rural communities that depend heavily on natural resource extraction from forests, fisheries, or mines. Rural roads are critical for increasing input and market access for crop and livestock farmers. Greater transport connectivity may reduce population turnover in some areas, depending on the time frame, demographics, education levels, and local and distant income and employment opportunities. This study did not find any consistent relationship between greater road connectivity and livelihood diversity. Perz *et al*. (2012) also found that increased road connectivity was associated with various negative social outcomes, such local people's reduced access to natural resources and an increased risk of forest fires (but also increased effectiveness of forest fire suppression). New or improved roads can also increase travel between rural and urban areas, which can contribute to migration from rural areas, especially by younger people.

5. RELATIVE MAGNITUDE OF GHG EMISSIONS FROM ROAD CONSTRUCTION, LAND USE CHANGES, AND ROAD USE

GHG emissions from vehicle use of roads are calculated by multiplying the projected use of different categories of vehicles by the average emission rates for each category of vehicle. Data on national GHG emissions from transportation can be obtained from a country's GHG inventory submission to the UNFCCC. However, downscaling national data or assumptions to estimate the GHG emissions from a particular road is problematic because emissions from a particular section of road depend on the local situation and detail about local geology, population, and human activities are needed to estimate local emissions.

The direct GHG emissions from construction materials and equipment use for road construction are generally greater than the emissions associated with the land cleared for the road. The direct emissions from constructing one kilometer of a four-lane highway have been estimated at 1,060-9,626 tCO_2e (see Section 4.1).

Road construction can also generate indirect GHG emissions due to associated deforestation and other land use changes that can occur many kilometers from the road. The indirect emissions can be much larger than the direct emissions from road construction and use. Reid (1999) estimated that construction of a new road through northern Bolivia would lead to 200 ha of deforestation per kilometer of the road. Gonzalez, Kroll, and Vargas (2013) estimated that deforestation would release 341 tCO_2e per hectare deforested in the Selva Central of Peru. Applying this emissions factor, the indirect emissions from road construction in the Madidi National Park would exceed 68,000 tCO_2e per kilometer of road construction. This is a conservative estimate because the Gonzalez, Kroll, and Vargas (2013) emission factor is at the low end of the range of default values in the IPCC Guidelines (2006). The default values for emissions from clearing the aboveground biomass in tropical moist forests were 330-532 tCO_2e/ha (180-290 metric tons of carbon per hectare).

The total GHG emissions from road vehicle use can exceed those from road construction in one to two years, depending on the types of vehicles used and the amount of traffic (Muench 2010). A heavily-used highway can carry 2,000 heavy vehicles per day in each lane.[2] The U.S. Department of Energy estimated the fuel efficiency of a new heavy truck in the U.S. at 5.75 miles per gallon. Based on these assumptions, the GHG emissions just from heavy trucks on a highway would be 1.0875 kg CO_2/km (Davis, Diegel, and Boundy 2015). It would take 1.25 years for emissions from heavy trucks to reach a low-end estimate of highway construction emissions of 1,000 tCO_2e per lane-kilometer. The EPA (2016) estimated an emission rate of 0.255 kg CO_2/km for the average passenger car in the United States. Including heavy trucks and passenger cars, the GHG emissions from use of a new highway in the U.S. would reach the low-end estimate of road construction emissions in 9.5 months.

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[2] Heavy trucks were defined here as having a weight of at least 11.8 metric tons.

Traffic can be heavy on rural highways that connect urban centers in developing countries. Omenda (2010) reported that typical daily traffic on the heavily used highway between Nairobi and Mombasa in Kenya was 5,000 light vehicles and 2,000 heavy trucks.[3] It may take time for a new highway in a developing country to reach these traffic levels. GHG emissions from vehicle use would be lower on less heavily used roads.

Rural roads in developing countries that are lightly used may carry fewer than 100 vehicles per day (Reid 1999). At this low usage level, it would take 26 years for vehicle emissions to equal the low-end estimate of road construction emissions. This estimate was based on average fuel efficiencies of heavy and light vehicles in the U.S. and the assumptions that half the vehicles were light and half are heavy. It would take over 100 years for vehicle emissions from use of a two-lane highway to exceed the high-end estimate of highway construction emissions from Kim *et al.* (2011). However, cars and trucks tend to be older, less fuel-efficient, and less well maintained in developing countries than in the U.S. and are likely to have higher GHG emissions per kilometer traveled.

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[3] Light vehicles were defined as having a weight less than 3,855 metric tons (8,500 pounds). Heavy vehicles exceeded this weight threshold.

6. TOOLS AND METHODS FOR ASSESSING THE IMPACT OF ROADS

6.1 TOOLS AND METHODS FOR ASSESSING DEFORESTATION AND FOREST DEGRADATION RISKS

Many complex, interacting factors affect the associations between road construction or improvement and deforestation and forest degradation. Differences in local conditions may make it difficult to generalize across locations. Meta-analyses can provide stronger support for these associations if findings are similar across many independent studies report but still might not reflect local conditions at another site. However, the emissions may change over time with increasing road usage and average vehicle fuel efficiency. The indirect impacts of roads on deforestation and forest degradation may change with other variables, such as soil quality or changes in international demand and supply for farm and forest products.

Randomized control experiments are not feasible for research on the relationship between roads and forest loss because of high planning and capital investment costs and the difficulty of establishing comparable control areas. Quasi-experimental methods — such as the "difference in differences" approach of Campbell and Stanley (1966) — might be feasible. Use of the difference-in-differences approach for this research would include a comparison of multiple sites over time for baseline conditions, forest resource outcomes, and the presence or absence of road construction or improvements. Although other factors are not controlled for in this quasi-experimental design, it may be reasonable to assume that they will net out if the number of study sites is large and randomly selected. Nevertheless, it is also unlikely that a large quasi-experimental study on the association between roads and forests will be carried out over an extended period of time.

The following questions are important in assessing the risks of deforestation and forest degradation from road construction or improvement:

- Will a new road be constructed? What is the road's total length, width, and vehicle capacity?
- Will an existing road be expanded? What is the road's increase in length, width, and vehicle capacity?
- Will the road connect areas with large populations or markets?
- Will the road be paved?
- Has the area already experienced significant deforestation or forest degradation? If so, are there still extensive forests?
- Is the road near a designated protected area that is effectively managed for conservation? Are there buffer zones with some land use restrictions around the protected area?
- Does the area have good potential for agriculture?
- Does the area have steep slopes or high elevations?

- How frequent are extreme weather events and if so, what are their types and magnitudes? How do they affect the road and other land areas in its zone of influence?

Table 2 contains a framework for assessing the magnitude of deforestation and forest degradation risks from road construction or expansion.

TABLE 2. Framework for Assessing the Magnitude of Deforestation and Forest Degradation Risks from Road Construction or Expansion

High Risk	Medium Risk	Low Risk
• New road built to a high standard of construction (paved) • Road connects areas with large populations • Road opens up major new markets (domestic or export) • Extensive forest resources remaining in the area • Absence of protected forest areas • Good agricultural potential • Relatively flat terrain • Low elevations • High pressures on land for human settlements, infrastructure, energy, or mining	• New road built to a medium standard of construction (gravel) • Major improvement of existing road • Road connects areas with moderate populations • Road connects to medium-size markets (domestic) • Moderate forest resources remaining • Designated protected area with weak enforcement • Moderate agricultural potential • Moderately steep slopes • Moderately high elevations • Moderate pressures on land for human settlements, infrastructure, energy or mining	• New road built to a low standard of construction (dirt) • Moderate improvement of existing road • Road connects areas with low populations • Road connects to small markets (domestic) • Few forest resources remaining • Protected areas with good enforcement • Low agricultural potential • Steep slopes • High elevations • Low pressures on land for human settlements, infrastructure, energy or mining

A proposed road will often have a mix of low-, medium-, and high-risk attributes for deforestation and forest degradation. For example, the proposed paving of Highway BR-319 in Brazil is an improvement to an existing road that connects two large population centers. The area had extensive forest resources and limited conservation protection. Annex A contains a case study on this proposed road.

Hewson, Steininger, and Pesmajoglou (2014), GOFC-GOLD (2013), and Milne *et al.* (2012) discussed methods for estimating forest carbon stock changes from remote sensing images. Aerial photographs provide detailed information on forest cover, but were not available for many locations or time periods as is available in satellite images. It takes much longer and may cost more to analyze aerial photographs covering the same area of land as satellite images. Automated processes for analyzing aerial photographs are in development though not commonly used. For more accurate estimates of changes in the forest carbon stock, satellite images of land cover can be combined with maps showing land uses, soils, productivity or production, elevation, and slope.

The World Resources Institute's online Global Forest Watch database contains data from high resolution satellite imagery with each pixel representing an area of 30 meters by meters. Hansen, Stehman, and Potapov (2010) discussed the methods used to arrive at the estimates. Landsat images with a pixel size of 30m x 30m generally cannot detect forest degradation involving less than 15 percent of the biomass.[4]

Restivo, Shandra, and Sommer (2017) conducted a statistical analysis of the Global Forest Watch data across countries. They found that deforestation was positively correlated with both agricultural and forestry exports and the location of forests within 10 km of roads. They also found that countries in the tropics had higher rates of forest loss. These correlations were all statistically significant.

Higher resolution satellite images and the combination of Landsat images with Light Detection and Ranging (LIDAR) to estimate tree heights can allow more precise carbon stock measurement (Asner *et al.* 2010; Sexton *et al.* 2013; Caughlin *et al.* 2016).[5] Satellite images with resolutions as fine as 0.41 m are commercially available, though they can be costly and only provide a limited historical record. As a result, very high-resolution data is often purchased for a limited geographic area. LIDAR can also be costly since airplanes are used in collecting the data and substantial expertise is needed for analysis. LIDAR is generally only cost-effective for tens of thousands of hectares or more (Messinger, Asner, and Silman 2016). New, lower cost methods use unmanned aerial vehicles (drones) to measure forest biomass (Mlambo *et al.* 2017).

Ground-based sampling is less expensive than a combination of remote sensing and LIDAR for analyzing forest cover over small areas, such as a radius of a few kilometers around a road. Ground-based sampling typically involves a few hundred measurement plots stratified by distance from the road and population centers. This process must be repeated to track forest biomass changes over time. Hewson, Steininger, and Pesmajoglou (2014); Howard *et al.* (2014); and McRoberts *et al.* (2013) provided guidance on designing ground sampling systems for forest carbon.

More precise data on changes in vegetative cover are needed to quantify forest degradation than are needed to quantify deforestation. Appropriate methods for estimating forest degradation depend on the size of the land area and available resources. Forest degradation can be measured over millions of hectares through LIDAR on the vegetative cover at different heights above the ground, but the data analysis is complex (Asner *et al.* 2010). On a smaller scale, ground-based measurement of forest degradation and regrowth is less costly and uses more readily available equipment and skills. Field data analysis can be difficult if vegetation patterns are complex and the climate is changing. Models have generally been used to estimate total biomass from tree diameter, height, and species composition, but local coefficients may be needed since these relationships can vary. Methods for converting tree biomass to carbon stocks are relatively simple.

6.2 TOOLS AND METHODS FOR ASSESSING ECONOMIC AND SOCIAL IMPACTS

Many transportation models are available for assessing the economic and social impacts of roads, based on location-specific economic and population data. Archondo-Callao (2004) prepared a user guide for the World Bank's *Roads Economic Decision Model* tool.

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[4] Landsat, a joint effort of NASA and the U.S. Geological Survey has provided remote sensing images of land globally for over 40 years.

[5] Light Detection and Ranging (LIDAR) measures the distance to a target using pulses of light. It has been used to measure elevation, tree canopy height, and biomass.

Use of these planning tools often requires generic assumptions since *ex post* data on the actual social and economic impacts of roads are usually unavailable in developing countries. Even if these data are available, they are likely to pertain to a different location or time period and may be difficult to obtain.

The economic benefits of a road are the difference between the Gross Domestic Product (GDP) with the road and without it for each year of its expected life. GDP projections require many assumptions about all final goods and services in an economy and are subject to considerable uncertainty. The projected annual differences are discounted to reflect the time value of money. The selection of the discount rate can make a large difference in whether an investment has a net economically favorability compared to alternative resource uses.

Computable general equilibrium (CGE) models and input-output analysis are two approaches to estimating GDP changes in response to major differences in economic conditions. The net economic effects could be estimated with a CGE. However, CGE models are costly to develop but an existing model may be available in some countries; they also require considerable expertise and data. Generally, CGE models are used only for analyzing the economic impact of major policies.

An input-output model is a much simpler alternative to the CGE, but the assumed linear relationships do not provide a dynamic representation of an economy and the underlying data may also be obsolete. If data are available, a sub-country level input-output analysis can also address regional development impacts.

Most CBAs of roads use simpler, partial equilibrium approaches that do not address the entire national or sub-country regional economy or consider the effects on all producers, consumers, and governments. Instead, CBAs typically estimate the present value of net economic benefits for a limited number of major producer and consumer groups. For example, a CBA might focus on increases in the value of agricultural and forest production due to access to more remunerative urban markets and reductions in transport costs for inputs and products.

Some CBAs have used changes in land values associated with new or expanded roads as a proxy for future economic benefits. This hedonic pricing approach uses a statistical analysis of changes in land values from other similar roads in relation to site characteristics and distance to roads. However, land prices may rise in anticipation of future road development or expansion as soon as construction plans have been announced or first discussed. Furthermore, changes in land prices only reflect the net income gains of landowners, not providers of labor and capital. As a result, property value changes will underestimate the increase in GDP to all factors of production. Also, increases in local land prices do not reflect any negative economic or environmental impacts associated with roads (externalities).

7. OPTIONS FOR REDUCING NEGATIVE IMPACTS OF ROADS

7.1 PROTECTED AREAS

The impact of protected area designation on the relationship between roads and deforestation or forest degradation depends on the type of protected area, legal protections provided, financial resource allocations, and the effectiveness of implementation and enforcement of the legal protections. The International Union for Conservation of Nature has defined seven categories of protected areas with varying degrees of conservation and use. This classification is in widespread use internationally (International Union for Conservation of Nature 2017):

> *Ia. Strict Nature Reserve:* Set aside to protect biodiversity and also possibly geological/ geomorphical features, where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values. These areas can serve as indispensable reference areas for scientific research and monitoring.
>
> *Ib. Wilderness Area:* Usually large unmodified or slightly modified areas, retaining their natural character and influence without permanent or significant human habitation, which are protected and managed so as to preserve their natural condition.
>
> *II. National Park:* Large natural or near natural areas set aside to protect large-scale ecological processes, along with the complement of species and ecosystems characteristic of the area, which also provide a foundation for environmentally and culturally compatible, spiritual, scientific, educational, recreational, and visitor opportunities.
>
> *III. Natural Monument or Feature:* Areas set aside to protect a specific natural monument, which can be a landform, sea mount, submarine cavern, geological feature such as a cave or even a living feature such as an ancient grove. They are generally quite small protected areas and often have high visitor value.
>
> *IV. Habitat/Species Management Area:* Areas to protect particular species or habitats as a management priority.
>
> *V. Protected Landscape/ Seascape:* Areas where the interaction of people and nature over time has significant, ecological, biological, cultural and scenic values that need to be safeguarded.
>
> *VI. Protected area With Sustainable Use of Natural Resources*: Areas where ecosystems and habitats have cultural values and traditional natural resource management systems. They are generally large, with most of the area in a natural condition, where a proportion is under sustainable natural resource management and low-level nonindustrial use can be compatible with nature conservation.

International designations of environmentally important areas include biosphere reserves under the United Nations Educational, Scientific and Cultural Organization (UNESCO) Man and the Biosphere Program and wetlands of international importance under the Ramsar Convention (http://www.ramsar.org/sites-countries/the-ramsar-sites) may encourage governments to establish protected areas and may help leverage donor funding.

There are also international designations of important biodiverse areas that do not bring legal protections or donor funding. Examples include important birding areas designated by BirdLife International, important plant areas designated by Plantlife International, and prime butterfly areas. Some of these locations have been identified as important areas in danger.

In general, deforestation associated with roads tends to be lower in designated protected areas (Barni, Fearnside, and Graça 2009; Ferretti-Gallon and Busch 2014; Gonzalez, Kroll, and Vargas 2014; Yanai *et al.* 2012). Ferretti-Gallon and Busch (2014) conducted a meta-analysis of 117 studies of the drivers of deforestation. Although most protected areas in developing countries have strict limits on natural resource extraction and land use in laws or regulations, national or subnational governments do not have sufficient resources or capacity to enforce them effectively. This is often the case in areas that are remote or have high commercial potential or population pressures. Some areas may have low agricultural production due to unfavorable soils, terrain, or climate. These areas may have a lower risk of deforestation, whether they have protected area status or not (Ferraro, Hanauer, and Sims 2011; Andam *et al.* 2008). However, some protected areas are managed by governments or parastatals for forestry and mining production or recreational uses that may contribute to deforestation or forest degradation. An example of allowed extractive uses contributing to deforestation is some reserves in Serbia.

Bare, Kauffman, and Miller (2015) claimed that the amount of conservation aid was paradoxically correlated with the area of lost forest losses after one- or two-year lags in 42 Sub-Saharan African countries between 2000 and 2013. They also found that the extent of protected areas was correlated with deforestation elsewhere in the country, which they attributed to possible displacement effects. However, these findings could reflect reverse causality; more donor funding during the study period was channeled to countries with high deforestation rates due to increased environmental concern and good aid targeting. Similarly, national governments in the region and their donors may have expanded protected areas most in high deforestation countries.

There is conflicting evidence on whether community ownership or resource use rights for forests are associated with lower or higher deforestation rates, after controlling for other factors. Ferretti-Gallon and Busch (2014) found mixed results in their literature review on whether community forestry was associated with increased deforestation; nine studies reported a decrease in deforestation and 11 studies reported an increase. Sustainable community forestry activities may help maintain forest cover. However, community control of land can increase deforestation by increasing access to capital and opportunities to convert land to pasture or agriculture. The relationship between deforestation and community ownership differs across countries and forest types.

7.2 TRANSPORTATION NETWORK PLANNING

Without good transportation planning, more road construction may happen than is necessary to meet the demand for transportation, resulting in greater deforestation or forest degradation (Patarasuk 2013). Transportation planning can reduce the number and length of roads needed for efficient movement of goods and people, lowering road development, construction, and maintenance costs.

Transportation planning begins with mapping all modes of transport and collecting current use rate data. Future use rates are projected under various scenarios of changes in population, income, and economic activity by location. The process of transportation planning also includes an analysis of alternative types, sizes, and locations of roads and their financial costs and travel time relative to other transportation modes. Computerized models can show whether road construction or improvement are economically beneficial and fiscally sound (Patarasuk 2013).

Good transportation planning is particularly important because road construction is often proposed for political or institutional reasons to gain votes in elections, reward contractors and other political supporters, fully use budgeted funds, or provide opportunities for rent-seeking behavior by officials. Although road construction and expansion are often proposed to promote subnational equity or poverty alleviation objectives, there may be other less costly or most effective ways to achieve these objectives.

Reid (1999) analyzed two proposed unpaved roads in rural Bolivia (150 km and 450 km, respectively) and found that expected use rates were low relative to the construction and maintenance costs. As a result, the net present values of these two roads were negative: -$16 million and -$24 million, respectively. Including the environmental costs from deforestation associated with the roads made the net present values more negative: -$61 million and -$111 million.

Paved road construction is more likely to increase economic activity in more developed areas (De Luca 2007). These areas may have higher population densities or greater potential for selling high-value products. In rural areas, the extension of low-standard feeder roads (farm-to-market roads) may reduce poverty more than the construction of paved roads. Roads generally get more use if they connect areas with substantial economic activity, such as two or more cities or a city and a port or rail hub.

Planners should conduct an independent environmental impact analysis and CBA that quantifies environmental risks and costs and make the findings available to the stakeholders. Planners should consider environmental impacts in selecting transportation alternatives. Caro *et al.* (2014) recommended strategies for minimizing the negative impacts of roads on key stakeholders, protected areas, and wildlife:

- In the early stages of road design, consult with natural resource managers to identify routes that reduce negative impacts on wildlife and ecosystem functioning;
- Avoid areas of high conservation value, including migration routes and dispersal corridors;
- Consult with key stakeholders early on and bring in an independent expert to review and suggest alternatives that cost less or have fewer negative environmental or social impacts;
- If a planned road passes through an important wildlife area, reduce negative environmental or social impacts by limiting traffic speeds, volume, and timing of traffic (such as slowing or reducing traffic during times of the year or times of the day when wildlife cross roads more frequently); and
- Analyze siting and design alternatives and modes of transportation that may be less costly or have fewer negative impacts.

The relationship between road construction or expansion and deforestation and forest degradation risks will vary by location and economic, demographic, environmental, and political conditions. Estimating the risks of a specific road is complex and subject to considerable uncertainty.

Greater reliance on rail or ship transport instead of roads could result in less deforestation, especially in areas with extensive forested areas. Roads increase the accessibility of forests along their entire length, while trains may only make forests more accessible around stations. Moreover, new or expanded primary roads may increase the demand for new secondary roads (Viana *et al.* 2008). Government officials may also have greater control over the location of train stations and could use this authority to reduce the risks of deforestation or forest degradation. Similarly, it may be possible to control shipping ports and routes for river and marine transport to reduce access to forests, depending on river navigability, ocean conditions, and potential landing sites.

Furthermore, the average GHG emissions from rail shipments are only one-fifth of the amount from truck transport per ton-mile of freight.[6] The capital costs are higher for new of rail transport infrastructure than for the same length of highway. Rail shipments may be more costly than trucking for short distances because of the costs of getting goods to and from the rail line. However, rail shipments may be less expensive than trucking for long distances.

7.3 INTEGRATING ROADS AND AGRICULTURAL PRODUCTIVITY ENHANCEMENTS TO REDUCE DEFORESTATION

Multiple analyses based on modeling have concluded that increased agricultural productivity on existing farmlands can reduce GHG emissions (Hertel 2012; Jones and Sands 2013; Carter *et al.* 2015; Lamb *et al.* 2016). While this may be possible, there is little empirical evidence that increases in agricultural productivity have reduced deforestation. Agricultural intensification can increase GHG emissions if it increases the use of nitrogen fertilizers or expands livestock production.

If productivity gains increase the profitability of crop and livestock production and sufficient markets, land, and resources are available, there will be a greater incentive to convert more forestland to agriculture (Hertel 2012; Ferretti-Gallon and Busch 2014). De Luca (2007) found that new roads, especially secondary feeder roads, increased agricultural productivity particularly where it was low (2007). Improvement of existing roads increased growth in nonagricultural activities more than agriculture. Well-designed and enforced forest policies are needed to reduce the conversion of forests to agricultural land in countries with considerable remaining forest cover (Ferretti-Gallon and Busch 2014; Carter *et al.* 2015).

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[6] The GHG emissions of trucks and rail were estimated from their relative energy consumption per unit weight of freight and the distance travelled. The energy consumption of trucks was estimated calculated by dividing 21,540 BTU/vehicle-mile (Davis et al., 2015) by 27 tons of payload per truck (Davis et al., 2015) and then dividing by a 0.57 truck utilization rate by weight (Hosseina and Shiran, 2011). These assumptions resulted in truck energy consumption rate of 1,400 BTU/ton-mile. Rail energy used 296 BTU/ton-mile in 2013 (Davis et al., 2015). These estimates assumed that heavy trucks and trains were diesel powered.

ANNEX A: DEFORESTATION PROJECTIONS FOR HIGHWAY BR-319 IN BRAZIL

The Government of Brazil (GoB) began construction of Highway BR-319 in 1968 and completed it in 1973, though it was not inaugurated until 1976. This 885-km highway extended from Porto Velho in Rondonia State to Manaus in Amazonas (Figure A-1). The area contained large amounts of primary forest. There was relatively little human settlement along some of the route, especially in the northern section below Manaus.

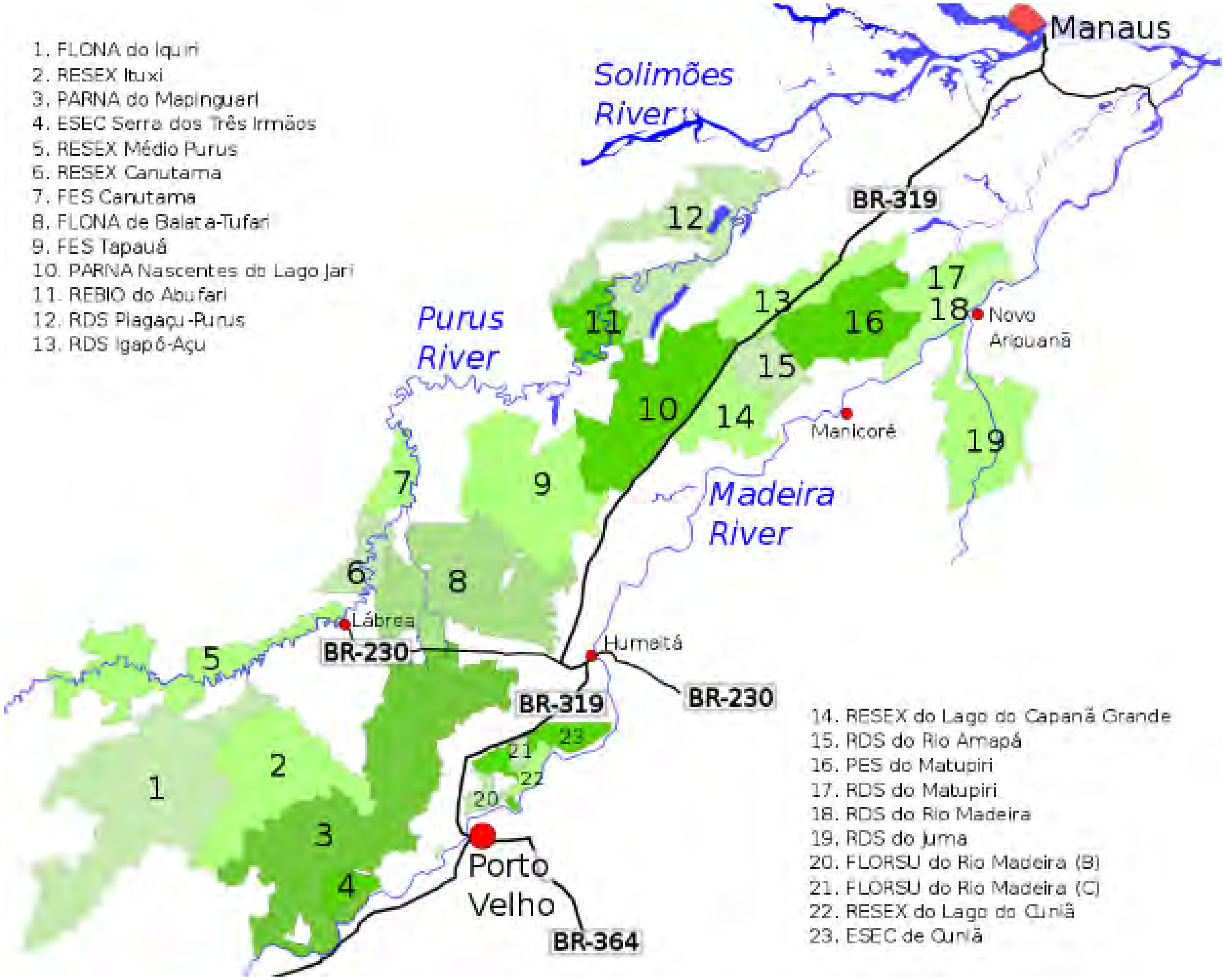
This highway had little traffic in the 1970s and 1980s. In addition, it was cheaper to transport industrial products from Manaus by boat along the Madeira River or by air freight. The construction specifications for Highway BR-319 were inadequate for the soil and climatic conditions. It was often unusable in the rainy season due to flooding, unstable clay soils, and landslides. The road was not well maintained and degraded quickly. It was largely impassable by 1986 and was abandoned in 1988 (Fearnside and Graça 2006; Cassola 2011). A 406-km section would have to be entirely reconstructed while other areas required extensive paving and bridge rebuilding (Cassola 2011).

Soares-Filho *et al*. (2006) projected the forest cover around BR-319 in 2030 and 2050 under four scenarios: 1) an increase in protected areas without paving the highway; 2) an increase in protected areas with the paving of the highway; 3) no increase in protected areas and no paving of the highway; and 4) no increase in protected areas with the paving of the highway (2006). They estimated that repaving the BR-319 could lead to a cumulative loss of nearly 89,000 km^2 of forest by 2050. However, they concluded that governance improvements (such as increasing protected areas) could reduce the deforestation rate whether or not BR-319 was paved (Figure A-2).

Soares-Filho *et al*. (2006) also estimated the total deforestation from paving BR-319 along with two other highways in the Brazilian Amazon — BR-163 (between Cuiabá and Santarém) and the Brazil Interoceanic Highway. Together, these three highways could lead to the loss of 2.1 million km^2 of closed-canopy forest in the Amazon by 2050 if no new protected areas were established, a 40 percent decrease from 2003 levels. If the protected area increased from 32 percent to 41 percent, the projected loss of closed-canopy forest was reduced to 800,000 square kilometers.

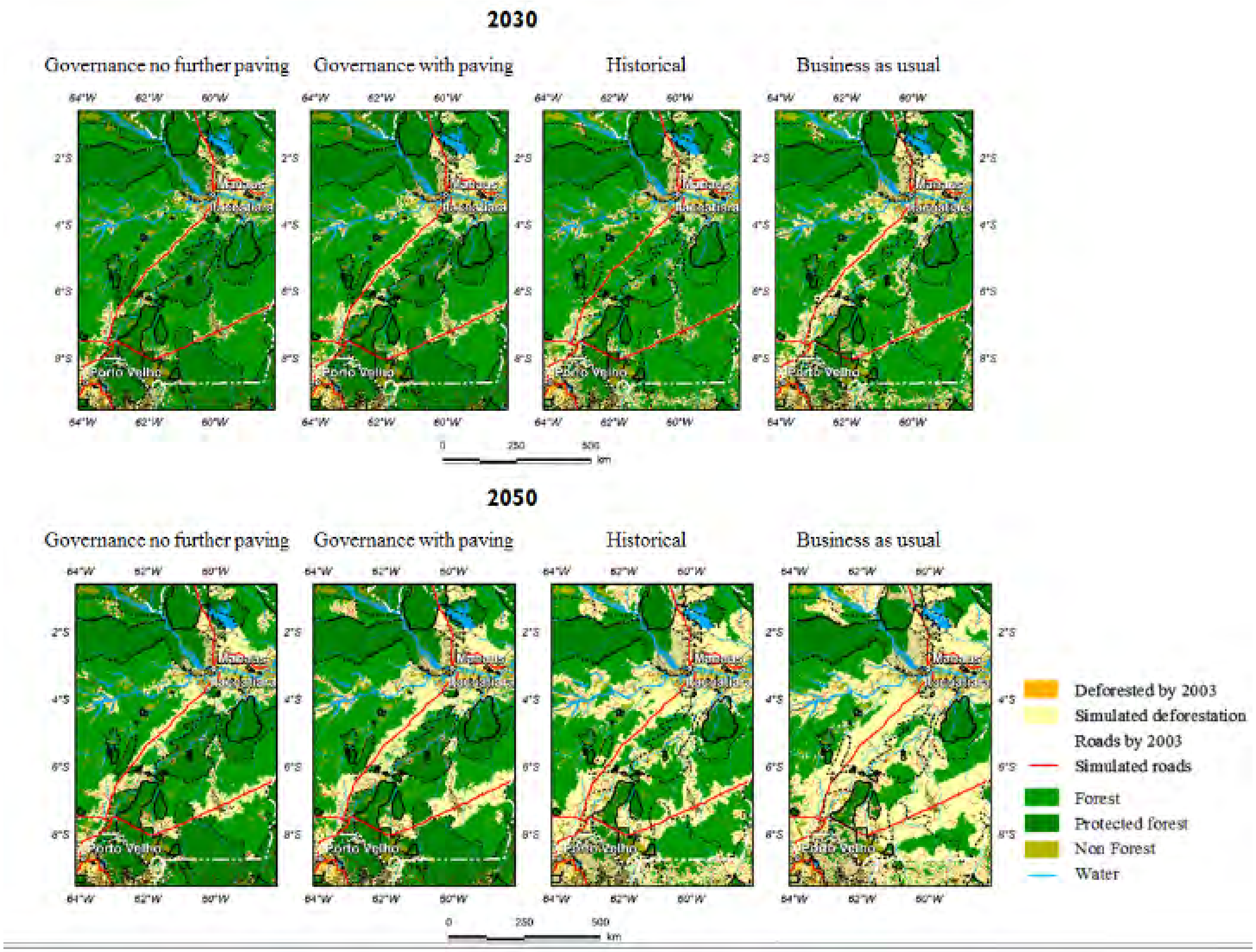
Viana *et al*. (2008) noted that rail could meet the transportation demands with less deforestation than BR-319 reconstruction as rail infrastructure only opens access to land around train stations. In contrast, roads increase access to land along their entire length and highways tend to induce a fishbone pattern of deforestation from side roads or paths. Train travel is also more fuel-efficient than trucks for transporting goods, though vehicle operating emissions tend to be a much smaller source of GHG emissions than roads. Viana *et al*. (2008) estimated that a rail corridor along BR-319 would cost $1.15 billion — 2.5 times the $450 million reconstruction costs for the highway. However, operating and maintenance costs would be lower for rail than roads.

FIGURE A-1. Map of Highway BR-319 from Porto Vehlo to Manaus (Protected Areas in Green)



Source: Wikimedia Commons, Aymatth (2016).

FIGURE A-2. Projected Deforestation in 2030 and 2050 from Paving BR-319



Source: Soares-Filho *et al.* (2006).

Barni, Fearnside, and Graça (2009) estimated that repaving Highway BR-319 would increase cumulative deforestation and GHG emissions between 2007 and 2030 if no additional measures are taken to conserve forests. However, they concluded that cumulative deforestation and GHG emissions could be lower than the baseline if forest conservation measures were implemented along with road repaving (Table A-1). These conservation measures included the establishment of 6,950 km^2 of national conservation units (fully or partially protected areas) in Roraima and policies to prevent new settlements and limit the expansion of existing settlements.[7] Barni, Fearnside, and Graça (2009) did not state whether these conservation units would be fully protected or allow timber harvesting. The business-as-usual scenario assumed no new conservation units or limits on new or existing settlements. The assumptions on migration rates were not specified in the three scenarios.

Fleck (2009) prepared a CBA of BR-319 reconstruction over a 25-year period under two scenarios. The conventional scenario included capital and maintenance costs and regional benefits from the cost and time savings in cargo and passenger transport. However, it did not account for the costs of deforestation.

The "integrated scenario" also considered the 1) option value of forests for pharmaceutical bioprospecting, 2) existence value (willingness to pay for biodiversity conservation), and 3) indirect use benefits from carbon storage. The integrated scenario was based on the following assumptions: 1) 4,613,400 ha of additional deforestation induced over the study period (based on Soares-Filho *et al.* 2006); 2) an option value for pharmaceutical bioprospecting of $0.20/ha/y, the low-end of the range estimated by Simpson *et al.* (1996); 3) an existence value of $31.20/ha/y from adjusted benefit transfer by da Motta (2002) based on Horton *et al.* (2002); and 4) a very low estimate of the global carbon storage value, \$0.16/tCO_{2e}, from the meta-analysis by Tol (2008). Nevertheless, the carbon storage value constituted over 72 percent of the three types of values of avoided deforestation included in the analysis. No direct use values were counted for timber harvesting or ecotourism.

Fleck (2009) reported that BR-319 reconstruction was *not* economically viable under either scenario. Economic viability requires a discounted-benefit cost ratio greater than 1.00 or equivalently, a *positive* net present value. Under the conventional scenario, the discounted benefit-cost ratio ranged from 0.33 at a discount rate of 12 percent to 0.72 at a discount rate of three percent. At the 12 percent discount rate, the net present value was a *negative* $150 million. Under the integrated scenario, the discounted benefit-cost ratio was 0.065 and the net present value was a *negative* $1,050 million.

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[7] Federal Law 9.985/2000 established a National System of Units of Conservation (Sistema Nacional de Unidades de Conservação or SNUC). It authorized two categories of protected areas: 1) *full protection* -- ecological stations, biological reserves, national parks, natural monuments, and wildlife refuges; and 2) *sustainable use* -- environmental protection areas, areas of relevant ecological interest, national forests, extractive reserves, wildlife reserves, sustainable development reserves, and private natural heritage reserves.

TABLE A-1. Estimated Cumulative Deforestation and GHG Emissions from Reconstruction of Highway BR-319

Scenario	Description	Cumulative Deforestation, 2007-2030 (km^2)	Increase in Cumulative GHG Emissions, 2007-2030 (million tCO_2e)
Baseline	No repaving	3,478	N/A
Business as usual	Repaving and measures to reduce deforestation	5,100	99
Conservation	Repaving and measures to reduce deforestation	2,134	-89

Source: Barni, Fearnside, and Graça (2009).

Barni, Fearnside, and Graça (2015) concluded that BR-319 could stimulate a new wave of population migration in remote, southern Roraima State — 50 km north of the road's end in Manaus. This area was already connected to Manaus by Highway BR-174. However, BR-319 reconstruction would increase carbon emissions from deforestation in the area by 19 percent under a conservation scenario and 42 percent under a business-as-usual scenario by 2030.[8]

In 2016, approximately 70 percent of the population of 1.3 million in the vicinity of BR-319 was urban. The rural areas still contained considerable intact forest and much of it lacks conservation protection (Conservation International 2017). Reconstruction of BR-319 could connect this forest to the "arc of deforestation" associated with Highway BR-364 in Acre and Rondonia states. It is likely to increase internal migration in the northern area below Manaus, especially in Roraima State. That area has higher soil fertility than central Brazil and forests, which could encourage conversion of forests to agriculture.

Ritter *et al.* (2017) noted that the main area affected by BR-319 is the Madeira-Purus interfluve, which has one of the highest levels of intact biodiversity in Amazonia, including a high degree of endemic species (Py-Daniel *et al.* 2007 and Ribas *et al.* 2011). The Câmara Legislativa (2016) stated that establishment of conservation units was "very important" in 60 percent of the lower Madeira River region and a "priority" for another 39 percent of the area. Ritter *et al.* (2017) reported that most estimates of deforestation from BR-319 reconstruction only considered the area along the highway and not areas affected by new connecting roads or higher population migration. For example, AM-366 is a planned road that would branch off from BR-319, opening access to a large area of intact forest west of the Purus River (Graça *et al.* 2014).

The GoB announced plans to rebuild BR-319 in 1996 and 2005, but the plans were not carried out. Some limited repair work was done in 2008 and 2009, but there was no major reconstruction. In 2006, a federal decree established an Area under Provisional Administration Limitation (ALAP) on both sides of the road that only allowed authorized activities and public works. However, the highway's area of influence would extend 100 km beyond the ALAP and include 553,000 km^2 of land. In 2007, the Amazonas Secretariat for the Environment and Development commissioned a pre-viability study for a railroad and waterway improvements as an alternative to BR-319. The capital costs would be high, but

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[8] Between 2007 and 2014, deforestation decreased in the Brazilian Amazon due to establishment and enforcement of forest conservation regulations. FAO (2014) estimated that the deforestation rate in the Brazilian Amazon in 2010-2015 was only 28 percent of the rate in 2000-2005. However, deforestation rates have increased in Brazil since late 2014 due to higher economic growth and a reduced national government commitment to forest conservation (Butler 2015).

the Secretariat expected that some of the construction costs could be offset by carbon credits (van Dijck 2013).

The National Department of Transport Infrastructure (DNIT) prepared a CBA of BR-319 reconstruction. Livermore and Revesz (2013) criticized this analysis for 1) overoptimistic estimates of the road traffic; 2) inclusion of bus fares but not alternative air or boat transport fares as a benefit; and 3) assuming that river transport of grain, wood, and fuel would shift to road transport despite the lower costs of shipping bulky goods by boat. After correcting for these issues, Livermore and Revesz (2013) estimated that BR-319 construction would generate a net direct loss of $162 million plus $1.13 billion in costs from negative externalities.

Some areas at the southern and northern ends of the highway were reconstructed and paved, but the more environmentally sensitive central sections were not. In 2014 and 2015, maintenance on the central section of BR-319 included some wetland removal, wooden bridge repairs, the existing culvert replacement, roadside clearing, and the laying of a base for the road surface. In April of 2015, a 'maintenance' plan for the central section was approved and the proposed work was similar to reconstruction, but without the final paving.

In October of 2015, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) embargoed further work on the central section and issued a fine resulting from irregularities and environmental damage. A federal court reversed this fine in November of 2015. In April of 2016, IBAMA issued a license for repairs of the central section that was valid for one year. However, repaving of the central section was deferred until the completion of an EIA.

When the Federal Public Ministry met with representatives from IBAMA and DNIT in May of 2016, IBAMA expressed concern about what would be done to control land invasion, deforestation, and illegal mining. As of January 2018, the GoB had not approved permits for repaving the middle section of BR-319. However, concerns about the risks of a gradual reconstruction and reopening remained (Brandford and Torres 2018).

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